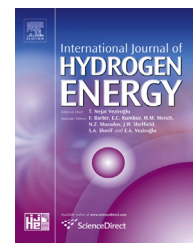


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A unified model of high-temperature fuel-cell heat-engine hybrid systems and analyses of its optimum performances

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ABSTRACT

On the basis of the models of various developed high-temperature fuel-cell heat-engine hybrid systems, a unified model of hybrid systems is proposed. General expressions for the power output and efficiency of hybrid systems, high-temperature fuel cells such as solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs), and heat engines including the Brayton, Otto, Diesel, Atkinson, Braysson, and Carnot engines are, respectively, derived by using the theories of electrochemistry and non-equilibrium thermodynamics. The effects of main irreversible losses existing in real fuel cells and heat engines on the performance of hybrid systems are investigated. The general performance characteristics and optimal operating regions of some of the key parameters of hybrid systems are discussed in detail. A variety of special typical cases are discussed. The important results in the literature can be readily reproduced, and the interesting findings of our study are presented.

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1. Introduction

In general, fuel cells can yield the highest efficiency and lowest emission for any known fossil-fueled power generation technology [1]. Consequently, they have received considerable attention in the world. Especially for high-temperature fuel cells, such as solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) [2,3], they boast advantages of coal and biomass gasification [4,5], fuel internal reforming [6,7], fuel flexibility [8,9], CO₂ capturing [10], high-quality heat coproduction [11], etc. However, high-temperature fuel cells

face some market entry challenges, ranging from the cost to the durability [12–14]. Researchers are making an effort in the development of suitable materials and fabrication of SOFCs [15–17], so that SOFCs could be suitable for small-scale residential market applications at sufficiently low cost of \$1000/kW [18]. A 3.5-kW SOFC cogeneration system for residential and commercial applications with an electrical efficiency of about 50% and overall efficiency of approximately 80% has been developed by Hydrovolt [19]. The cost of MCFCs is generally low in comparison with that of SOFCs when cheaper materials and inexpensive fabrication techniques are used.

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The power density of MCFC systems operating at 650 °C, however, is relatively low, and is approximately 1.5 kW m⁻² [20]. It follows that MCFC will likely be commercialized at sizes greater than 100 kW, and such commercialization will certainly increase the cost. Hence a more appropriate strategy is to develop smaller MCFC systems for distributed combined heat and power (CHP) applications with a typical electrical power output between 250 kW and 1 MW [20]. The cost of fuel cell systems can be reduced not only by better-quality materials [21–23] but also by further-advanced technologies [24] that include the integration of high-temperature fuel cells with heat engines.

For purposes of low pollutant emission and high fuel economy, a hybrid system including fuel cells and Diesel or Otto engines was proposed in 1999 [25]. Since up to a half of the fuel energy of high-temperature fuel cells is waste heat, numerous investigators have carried out the research on high-temperature fuel-cell based hybrid systems in order to increase the overall efficiencies of fuel cells. Research activities are exemplified by (a) using high-temperature fuel cells as topping units within gas turbine cycles [26,27], (b) overcoming lower performances of high-temperature fuel cells than those of low-temperature ones by constructing fuel cell-Carnot heat engine hybrid systems [28], (c) recovering waste heat from the cell by the design of SOFC-Stirling or MCFC-Stirling hybrid systems [29], and (d) proposing a Brayton-cycle thermal-management system to reduce the hydrogen fuel flow for cooling [30]. High-temperature fuel-cell based hybrid systems also include CHP systems, combined cooling, heat, and power (CCHP) systems [31,32], SOFC-proton exchanger membrane fuel cell (PEMFC) systems [33], and fuel-cell and Rankine or Kalina cycle hybrid systems [34–36].

The integration of heat engines and fuel cells are capable of not only recovering energy from fuel-cell exhaust gases, but also generating extra power. The efficiencies of SOFC- or MCFC-based hybrid systems can attain up to 70%–90% [37]. By comparing the technologies of fuel cells and internal combustion engines in vehicles, the former enjoys simpler designs, higher reliabilities, noiseless operations, higher efficiencies, less environmental impact, and lower energy consumption [38–40]. However, fuel cells may not supply sufficient energy during peak power demand periods and transient events, and cannot save power and recycle braking energy, either. The optimal combination of the fuel cell, internal combustion engine, and electric energy storage and conversion devices is proposed. It is more flexible with its efficiency being less load-dependent than individual units un-combined [25,41,42].

In the present paper, the general performance characteristics of high-temperature fuel cells, heat engines, and their hybrid systems are described. The advantages of hybrid systems are demonstrated in numerical results, with contents organized as follows. In Section 2, a unified model of high-temperature fuel-cell heat-engine hybrid systems is established. The power output and efficiency of hybrid systems are derived. In Section 3, some general performance characteristics of hybrid systems are revealed and their parametric optimal criteria are determined. Many interesting cases are discussed in detail in Section 4. The performance characteristics of several developed hybrid systems are presented. Finally, some important conclusions are drawn.

2. A unified model of high-temperature fuel-cell heat-engine hybrid systems

A generic hybrid system primarily consists of a high-temperature fuel cell and a heat engine, as shown in Fig. 1 [28,29], where the high-temperature waste heat generated in the fuel cell is utilized as the heat input of the heat engine, the waste gases produced in the fuel cell are used to preheat the fuel and the oxidant through a heat exchanger, P_e and P_h are the power outputs of the fuel cell and the heat engine, respectively, q_1 and q_2 are the rates of heat flow from the fuel cell at temperature T to the working substance of the heat engine and from the working substance of the heat engine to the environment at temperature T_o , respectively, and q_l is the heat leak rate from the fuel cell to the environment. Below, we first introduce the developed models of high-temperature fuel cells and heat engines, and then establish a unified model of high-temperature fuel-cell heat-engine hybrid systems.

2.1. Power output and efficiency of high-temperature fuel cells

When studying the performance of high-temperature fuel cells, one has to consider the thermodynamic and electrochemical irreversibilities which result from the activation overpotential (η_{act}), ohm overpotential (η_{ohm}), and concentration overpotential (η_{con}) [43,44]. A general equation

$$\eta_{act} + \eta_{ohm} + \eta_{con} = f\left(\frac{i}{i_0}\right) + i \sum_j \rho_j \delta_j - \frac{RT}{n_e F} \ln \left(\frac{p_{H_2} p_{H_2O,b} p_{CO_2,b}^{an} p_{CO_2}^{ca}}{p_{H_2,b} p_{H_2O} p_{CO_2}^{an} p_{CO_2,b}^{ca}} \sqrt{\frac{p_{O_2}}{p_{O_2,b}}} \right) \quad (1)$$

can summarize the three overpotentials of high-temperature fuel cells based on the theoretical and experimental results, where i and i_0 are, respectively, the current density and the exchange current density, ρ_j and δ_j are the specific resistivity and the flowing length in layer j , respectively, R is the universal gas constant, n_e is the number of electrons transferred in reaction, F is Faraday's constant, p_i ($i = H_2, H_2O, O_2, \dots$) is the partial pressure of component i , and $p_{i,b}$ is the partial pressure of component i in bulk phase on the surface of electrodes.

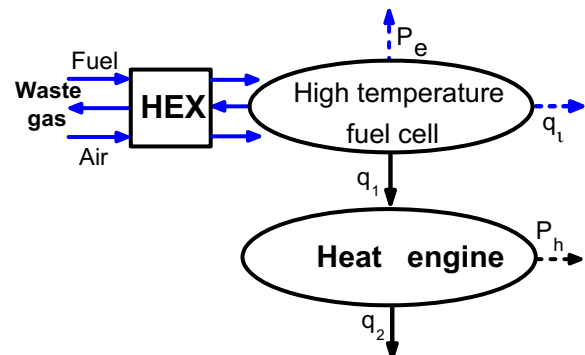


Fig. 1 – A schematic diagram of the unified model of high-temperature fuel-cell heat-engine hybrid systems.

Equation (1) can be expressed in several forms for differently working conditions, which can be seen from the following discussion for three overpotentials.

2.1.1. Activation overpotential

Activation overpotential occurs due to the energy barrier which must be overcome by reactants to allow the electrochemical reaction to happen. An accurate relation [45–48]

$$\frac{i}{i_0} = \exp\left(\frac{\alpha n_e F}{RT} \eta_{act}\right) - \exp\left[-\frac{(\alpha - 1)n_e F}{RT} \eta_{act}\right] \quad (2)$$

between the activation overpotential and the current density is derived from Butler–Volmer equation [49]. At high-activation polarization, Eq. (2) will be simplified into the Tafel expression [50,51]

$$\eta_{act} = \frac{RT}{\alpha n_e F} \ln\left(\frac{i}{i_0}\right), \quad (3)$$

while at low-activation polarization, Eq. (2) will then be simplified into the well-known linear potential–current relation [52,53]

$$\eta_{act} = \frac{RT}{n_e F} \frac{i}{i_0}. \quad (4)$$

Another linear relationship between the activation overpotential and the current density obtained by experimental approach is [54]

$$\eta_{act} = a \exp\left(\frac{b}{T}\right). \quad (5)$$

In Eqs. (2)–(5), α is the charge transfer coefficient of electrodes, a and b are two constants, and i_0 can be derived by a semi-empirical method and is given by [45–48,52,53]

$$i_0 = \gamma_0 (p_{H_2(CO)})^{a_1} (p_{H_2O})^{a_2} (p_{O_2})^{c_1} (p_{CO_2})^{a_3+c_2} \exp\left(-\frac{E_{act}}{RT}\right) \quad (6)$$

or [55]

$$i_0 = \gamma_0 (p_{H_2(CO)})^{a_1} (p_{H_2O})^{a_2} (p_{O_2})^{c_1} (p_{CO_2})^{a_3+c_2} \exp\left[\frac{E_{act}}{R} \left(\frac{1}{T_0} - \frac{1}{T}\right)\right], \quad (7)$$

where $c_1 = c_2 = 0$ for the anode, $a_1 = a_2 = a_3 = 0$ for the cathode, γ_0 is the coefficient of electrodes, E_{act} is the activation energy of electrodes, T_0 is the reference temperature of high-temperature fuel cells, and $p_{H_2(CO)}$, p_{O_2} , p_{H_2O} , and p_{CO_2} are the partial pressures of H_2 (CO), O_2 , H_2O , and CO_2 , respectively.

2.1.2. Ohm overpotential

Ohm overpotential occurs due to the resistance to the flow of ions in the electrolyte and the resistance to the flow of electrons through electrodes and interconnectors. By Ohm's law, the ohm overpotential existing in the anode, cathode, electrolyte, and interconnectors of high-temperature fuel cells is [47,56]

$$\eta_{ohm} = i \sum_j \rho_j \delta_j, \quad (8)$$

where ρ_j is dependent on the temperature T_j of layer j , which is [47,57,58]

$$\rho_j = a_j \exp\left(\frac{b_j}{T_j}\right), \quad (9)$$

while there are other expressions for the electrolyte' specific resistivity [59,60]

$$\rho_e = T_e a_e \exp\left(\frac{b_e}{T_e}\right) \quad (10)$$

or [61]

$$\rho_e = a_e \exp\left[b_e \left(\frac{1}{T_e} - \frac{1}{T_0}\right)\right]. \quad (11)$$

The specific resistivity of interconnectors can also be a constant to fit experiment data [29]. In Eqs. (9)–(11), a_j , b_j , a_e , and b_e are constants. If there is not a generally applicable mechanistic equation to calculate the total internal resistance caused by ohmic losses, the ohm overpotential can also be expressed as [62]

$$\frac{\eta_{ohm}}{i} = \gamma_1 + \gamma_2 T + \gamma_3 i + \gamma_4 T i + \gamma_5 T^2 + \gamma_6 i^2, \quad (12)$$

where γ_1 , γ_2 , ..., γ_6 are constants determined by experiment data.

2.1.3. Concentration overpotential

Concentration overpotential occurs when the diffusion rates of reactants and products through electrodes are slower than the electrochemical reaction [51]. For MCFCs, the reaction takes place at low polarization so that the concentration loss is negligible, compared with other losses [44,52]. The diffusion transport in a porous material can be described by Fick's model, dusty gas model, or Stefan–Maxwell model [63,64]. Fick's model, which is simple and is used more frequently, is adopted here. According to Fick's model, the concentration overpotential can be expressed as [46,65]

$$\eta_{con} = -\frac{RT}{n_e F} \ln \left[\left(1 - \frac{RT \delta_a i}{n_e F D_{H_2} p_{H_2,b}} \right) / \left(1 + \frac{RT \delta_a i}{n_e F D_{H_2O} p_{H_2O,b}} \right) \right] - \frac{RT}{2n_e F} \ln \left[\frac{p_{ca}}{p_{O_2,b}} - \left(\frac{p_{ca}}{p_{O_2,b}} - 1 \right) \exp\left(\frac{RT \delta_c i}{2n_e F D_{O_2} p_{ca}}\right) \right], \quad (13)$$

where δ_a and δ_c are, respectively, the thickness of anode and cathode electrodes, p_{ca} is the pressure of the cathode electrode, and D_{H_2} , D_{O_2} , and D_{H_2O} are, respectively, the effective diffusion coefficients of H_2 , O_2 , and H_2O , which depend on the temperature and the structure of fuel cells.

In some literature, Eq. (13) was simplified into [51]

$$\eta_{con} = -\frac{RT}{n_e F} \ln \left(1 - \frac{i}{i_{L,H_2}} \right) - \frac{RT}{2n_e F} \ln \left(1 - \frac{i}{i_{L,O_2}} \right) \quad (14)$$

or [42,45,56,57]

$$\eta_{con} = -\frac{RT}{n_e F} \ln \left(1 - \frac{i}{i_L} \right), \quad (15)$$

where i_{L,H_2} and i_{L,O_2} are, respectively, the limiting current densities at which the hydrogen and the oxygen are used up at a rate equal to their maximum supply speeds, and i_L is the limiting current density at these electrodes. There is another common expression to model the concentration overpotential [66], i.e.

$$\eta_{\text{con}} = m \exp(ni), \quad (16)$$

where m and n are constants.

The open-circuit voltage of high-temperature fuel cells is [51,67,68]

$$E = \frac{-\Delta g^0(T)}{n_e F} + \frac{RT}{n_e F} \ln \left(\frac{p_{H_2} p_{O_2}^{1/2} p_{CO_2}^{ca}}{p_{H_2O} p_{CO_2}^{an}} \right), \quad (17)$$

where $\Delta g^0(T)$ is the molar Gibbs free energy change of the chemical reaction at temperature T and standard pressure, and $p_{CO_2}^{ca}$ and $p_{CO_2}^{an}$ are the partial pressures of CO_2 at different electrodes, respectively. Considering the influence of irreversible losses above on the performance of high-temperature fuel cells, one can derive the power output and efficiency of high-temperature fuel cells as

$$\begin{aligned} P_e &= iA_c(E - V_{\text{act}} - V_{\text{ohm}} - V_{\text{con}}) \\ &= iA_c \left[\frac{-\Delta g^0(T)}{n_e F} + \frac{RT}{n_e F} \ln \left(\frac{p_{H_2} p_{O_2}^{1/2} p_{CO_2}^{ca}}{p_{H_2O} p_{CO_2}^{an}} \right) - f \left(\frac{i}{i_0} \right) \right. \\ &\quad \left. - i \sum_j \rho_j \delta_j + \frac{RT}{n_e F} \ln \left(\frac{p_{H_2} p_{H_2O,b} p_{CO_2,b}^{an} p_{CO_2}^{ca}}{p_{H_2,b} p_{H_2O} p_{CO_2}^{an} p_{CO_2,b}^{ca}} \sqrt{\frac{p_{O_2}}{p_{O_2,b}}} \right) \right] \end{aligned} \quad (18)$$

and

$$\begin{aligned} \eta_e &= \frac{P_e}{-iA_c \Delta h^0(T) / (n_e F)} \\ &= \frac{n_e F}{-\Delta h^0(T)} \left[\frac{-\Delta g^0(T)}{n_e F} + \frac{RT}{n_e F} \ln \left(\frac{p_{H_2} p_{O_2}^{1/2} p_{CO_2}^{ca}}{p_{H_2O} p_{CO_2}^{an}} \right) - f \left(\frac{i}{i_0} \right) \right. \\ &\quad \left. - i \sum_j \rho_j \delta_j + \frac{RT}{n_e F} \ln \left(\frac{p_{H_2} p_{H_2O,b} p_{CO_2,b}^{an} p_{CO_2}^{ca}}{p_{H_2,b} p_{H_2O} p_{CO_2}^{an} p_{CO_2,b}^{ca}} \sqrt{\frac{p_{O_2}}{p_{O_2,b}}} \right) \right], \end{aligned} \quad (19)$$

respectively, where A_c is the surface area of bipolar plates and $\Delta h^0(T)$ is the molar enthalpy change of the chemical reaction at temperature T and standard pressure.

2.2. Two modes of heat engine cycles

A survey of the developed heat engines has disclosed that there mainly exist two classes of heat engine cycles. The first class of cycles are composed of two isothermal and two polytropic processes such as the Carnot cycle consisting of two isothermal and two adiabatic processes [69], the Stirling cycle consisting of two isothermal and two isochoric processes [70], the Ericsson cycle which consists of two isothermal and two isobaric processes [71], etc. The performance of the hybrid systems composed of such a class of heat engines and high-temperature fuel cell has been analyzed [26,28,29,72]. The second class of cycles are composed of two polytropic and two adiabatic processes such as the Carnot cycle consisting of two isothermal and two adiabatic processes, the Diesel cycle consisting of an isobaric, an isochoric and two adiabatic processes [73,74], the Atkinson cycle consisting of an isochoric, an isobaric and two adiabatic processes [75,76], the Otto cycle consisting of two isochoric and two adiabatic processes [77], the Brayton cycle consisting of two isobaric and two adiabatic processes [78], the Braysson cycle consisting of an isobaric, an isothermal, and two adiabatic processes [79], etc. The performance of some of the hybrid systems composed of such a

class of heat engines and high-temperature fuel cells has been also analyzed [29,34,80].

On the basis of the cycle models of heat engines aforementioned, we can establish a generic cycle model of heat engines which include not only the second class of cycles mentioned above but also some new cycle modes, as show in Fig. 2, where q_1 and q_2 are the rates of heat flow absorbed from the heat reservoir at temperature T and released to the cold reservoir at temperature T_0 by the working substance during two polytropic processes 3–4 and 6–1, respectively, 1–2S and 4–5S are two reversible adiabatic processes, 1–2 and 4–5 are two irreversible adiabatic processes, 2S–4 and 5–1 are two polytropic processes, q_R is the rate of heat flow from regenerative process 5–6 to 2–3, and T_i ($i = 1, 2, 3, 4, 5, 6$) are the temperatures of the working substance at state points i . Assume that heat capacities of the working substance in two polytropic processes are, respectively, c_H and c_L . If $c_H = c_p$ and $c_L = c_v$, the cycle is the Diesel cycle, where c_p and c_v are the heat capacities of the working substance at constant pressure and volume, respectively; if $c_H = c_L = c_p$, the cycle is the Brayton cycle; if $c_H = c_L = c_v$, the cycle is the Otto cycle; if $c_H = c_p$ and $c_L \rightarrow \infty$, the cycle is the Carnot cycle; if $c_H = c_p$ and $c_L \rightarrow \infty$, the cycle is the Braysson cycle; if $c_H \rightarrow \infty$ and $c_L = c_p$, the cycle is a new cycle [81]; if $c_H = c_v$ and $c_L = c_p$, the cycle is the Atkinson cycle [82]. In addition, such a cycle model also includes the cycle mode of the turbine engine [83], which is often adopted in the high-temperature fuel-cell turbine-engine hybrid systems [24,26,57,84]. When the cycle is endoreversible, the performance of the Carnot cycle is the same as that of the Stirling and Ericsson cycles with the ideal regeneration [72]. It implies that the results obtained from the generic cycle model may be directly used to discuss the performance of the endoreversible Stirling and Ericsson cycles with the ideal regeneration.

When irreversibilities from non-ideal adiabatic and regenerative processes in the cycle are considered, one may obtain [85]

$$\dot{m} c_H \ln \frac{T_4}{T_3} \leq \dot{m} c_L \ln \frac{T_6}{T_1} \quad (20)$$

according to the second law of thermodynamics. So a parameter I may be introduced to describe the internal

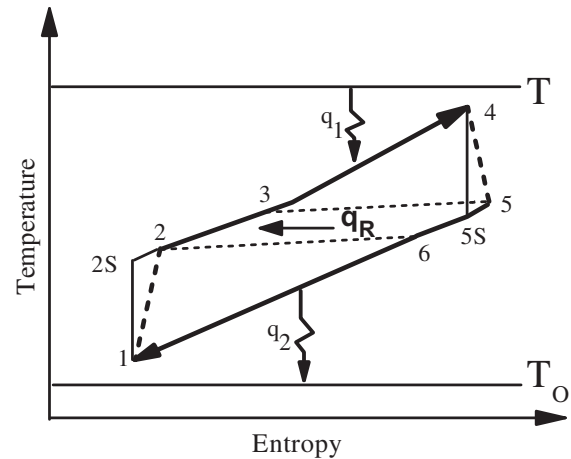


Fig. 2 – Temperature–entropy diagram of a generic cycle model of the heat engines consisting of two polytropic and two adiabatic processes.

irreversible losses of the working substance [86] and $0 < I = (T_1/T_6)(T_4/T_3)^{c_H/c_L} \leq 1$. When $I = 1$, the cycle is endoreversible. Some authors [87,88] have also defined the efficiencies of the compressor, turbine, and regenerator, respectively, to describe the internal irreversible losses of the cycle. If the efficiencies of these three processes are all equal to 1, the cycle is endoreversible.

Assume that the heat transfer between the working substance and heat reservoirs obeys the Newtonian law [89,90], one can obtain the heat flow rates in the cycle as [73,81]

$$q_1 = \frac{K_H A_H (T_4 - T_3)}{\ln[(T - T_3)/(T - T_4)]} = \dot{m} c_H (T_4 - T_3), \quad (21)$$

$$q_2 = \frac{K_L A_L (T_6 - T_1)}{\ln[(T_6 - T_0)/(T_1 - T_0)]} = \dot{m} c_L (T_6 - T_1), \quad (22)$$

and

$$q_R = \frac{K_R A_R [(T_5 - T_3) - (T_6 - T_2)]}{\ln[(T_5 - T_3)/(T_6 - T_2)]} = \dot{m} c_H (T_3 - T_2) = \dot{m} c_L (T_5 - T_6), \quad (23)$$

where K_H , K_L , and K_R are heat transfer coefficients in processes 3–4, 6–1, and 5–6, respectively, and A_H , A_L , and A_R are corresponding heat transfer areas. Combining Eqs. (21)–(23), one can obtain the efficiency and rewrite the rate of the heat input of the heat engine as

$$\eta_h = 1 - \frac{T_1[(T_4/T_3)^\gamma/I - 1]}{\gamma(T_4 - T_3)} \quad (24)$$

and

$$q_1 = \frac{AK_H(T_4 - T_3)}{\ln \frac{T - T_3}{T - T_4} + \frac{K_H}{K_R(\gamma - 1)} \ln \frac{\gamma(T_3 - T_1/x) + T_1(T_4/T_3)^\gamma/I - T_3}{(T_1(T_4/T_3)^\gamma)/I - T_1/x} + \frac{K_H}{\gamma K_L} \ln \frac{(T_1(T_4/T_3)^\gamma)/I - T_0}{T_1 - T_0}}, \quad (25)$$

respectively, where $A = A_H + A_L + A_R$ is the total effective heat transfer area of the heat engine, $\gamma = c_H/c_L$, and $x = T_1/T_2$.

In order to derive the maximum efficiency for a given rate of the heat input, we introduce a Lagrangian function as

$$L = \eta_h + \lambda q_1, \quad (26)$$

where λ is the Lagrangian multiplier. Using the extreme conditions

$$\begin{cases} \left(\frac{\partial L}{\partial T_1}\right)_{T_3, T_4} = 0 \\ \left(\frac{\partial L}{\partial T_3}\right)_{T_1, T_4} = 0 \\ \left(\frac{\partial L}{\partial T_4}\right)_{T_1, T_3} = 0 \end{cases} \quad (27)$$

and Eq. (25), one can obtain the optimum values $T_{1,\eta}$, $T_{3,\eta}$, and $T_{4,\eta}$ of T_1 , T_3 , and T_4 , respectively, for given $q_1/(AK_H)$, γ , I , x , K_H/K_L , and K_H/K_R . Substituting $T_{1,\eta}$, $T_{3,\eta}$, and $T_{4,\eta}$ into Eq. (24), one can obtain the maximum efficiency $\eta_{h,m}$ of the heat engine for a given $q_1/(AK_H)$.

2.3. Power output and efficiency of the unified model

As shown in Fig. 1, one part of the waste heat from the high-temperature fuel cell is released into the environment directly through conductive and/or convective heat transfer, and the other part is transferred into the heat engine. The heat leak rate may be expressed as [91]:

$$q_l = K_l A_l (T - T_0), \quad (28)$$

where K_l and A_l are, respectively, the heat leakage coefficient and effective area of the fuel cell. Combining the first law of thermodynamics and Fig. 1, one can obtain the heat input rate of the heat engine as [92]

$$q_1 = (-iA_c \Delta h^0(T)) / (n_e F) - P_e - q_l. \quad (29)$$

Combining Eqs. (19) and (28), one can rewrite Eq. (29) as

$$q_1/(AK_H) = b_1[(1 - \eta_e)i - b_2(T - T_0)], \quad (30)$$

where $b_1 = -A_c \Delta h^0(T)/(n_e F AK_H)$ and $b_2 = K_l A_l n_e F / (-A_c \Delta h^0(T))$.

Using Eq. (30), one can obtain the power output and efficiency of the hybrid system as

$$P = P_e + P_h = \frac{iA_c \Delta h^0(T)}{-n_e F} \left\{ \eta_e + \eta_{h,m} \left[1 - \eta_e - \frac{b_2(T - T_0)}{i} \right] \right\} \quad (31)$$

and

$$\eta = P / \left(\frac{iA_c \Delta h^0(T)}{-n_e F} \right) = \eta_e + \eta_{h,m} \left[1 - \eta_e - \frac{b_2(T - T_0)}{i} \right], \quad (32)$$

respectively. For SOFC-based hybrid systems, η_e in Eqs. (31) and (32) may be expressed as [48,93]

$$\begin{aligned} \eta_e = \frac{-RT}{\Delta h^0(T)} & \left[\frac{-\Delta g^0(T)}{RT} + \ln \left(\frac{p_{H_2} \sqrt{p_{O_2}}}{p_{H_2O}} \right) - 2 \sin^{-1} \left(\frac{i}{2i_{0,a}} \right) \right. \\ & - 2 \sin^{-1} \left(\frac{i}{2i_{0,c}} \right) + \ln \left(1 - \frac{i}{i_{L,H_2}} \right) + \frac{1}{2} \ln \left(1 - \frac{i}{i_{L,O_2}} \right) \\ & \left. - \frac{i n_e F}{RT} \sum_j \delta_j a_j \exp \left(\frac{b_j}{T} \right) \right], \end{aligned} \quad (33)$$

and for MCFC-based hybrid systems, η_e in Eqs. (31) and (32) may be expressed as [94–96]

$$\begin{aligned} \eta_e = \frac{-RT}{\Delta h^0(T)} & \left\{ \frac{-\Delta g^0(T)}{RT} + \ln \left(\frac{p_{H_2} \sqrt{p_{O_2}} p_{CO_2,ca}}{p_{H_2O} p_{CO_2,an}} \right) \right. \\ & \left. - \frac{i}{i_{0,a}} - \frac{i}{i_{0,c}} - \frac{i n_e F}{RT} \delta_e a_e \exp \left[b_e \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \right\}. \end{aligned} \quad (34)$$

3. General performance characteristics and parametric optimum criteria

Numerical calculations are carried out based on the parameters summarized in Tables 1 and 2 which can be derived from Refs. [48,93–95,97]. These parameters are kept constant unless otherwise mentioned specifically.

Combining Eqs. (24)–(27), (30), and (33), one can obtain the curves of $T_{1,\eta}$, $T_{3,\eta}$, and $T_{4,\eta}$ varying with the current density i for different given values of γ , as shown in Fig. 3. When the current density is small, $T_{1,\eta}$ and $T_{4,\eta}$ approach to T_0 and T , respectively. When the current density increases, the efficiency of the fuel cell decreases and the waste heat produced in the fuel cell increases. In order to efficiently utilize the waste heat, $(T_{1,\eta} - T_0)$ and $(T - T_{4,\eta})$ are required to increase with the increase of the current density, and $T_{3,\eta}$ decreases with the decrease of $T_{4,\eta}$ according to Eq. (21). Substituting $T_{1,\eta}$, $T_{3,\eta}$, and $T_{4,\eta}$ into Eq. (24), one can obtain the maximum efficiencies $\eta_{h,m}$ of various heat engines for a given heat input. Combining Eqs. (31)–(33), one can generate the curves of the power output and efficiency of SOFC-based hybrid systems varying with the current density, as shown in Fig. 4, where $P^* = P/A_c$ and $P_e^* = P_e/A_c$ [96]. It can be seen from Fig. 4 that the maximum power density of the SOFC is 6622 W m^{-2} , which is

situated between the experimental values of $5710\text{--}8830 \text{ W m}^{-2}$ [98,99]. Similarly, using Eqs. (24)–(27), (30)–(32), and (34), one can generate the curves of the power output and efficiency of MCFC-based hybrid systems varying with the current density, as shown in Fig. 5. It can be seen from Fig. 5 that the maximum efficiency of the MCFC is 0.74, which is situated between the experimental values of $0.4\text{--}0.86$ [100].

It can be seen from Figs. 4 and 5 that the performance of high-temperature fuel cells can be greatly improved by combining heat engines. For a high-temperature fuel-cell heat-engine hybrid system, there always exist one maximum power output P_{max} and one maximum efficiency η_{max} . When $i > i_p$, both the power output and the efficiency of the hybrid system decrease as the current density is increased. When $i < i_p$, both the power output and the efficiency of the hybrid system decrease as the current density is decreased. It shows that the current density i_η at the maximum efficiency and current density i_p at the maximum power output are, respectively, the lower and upper bounds of the optimized current density of the high-temperature fuel cell. Thus, the optimal region of the current density of the high-temperature fuel cell may not be arbitrarily chosen and should be situated in the range of $i_\eta \leq i \leq i_p$. Consequently, the optimum regions of the power output and efficiency of the hybrid system should be, respectively, situated in the range of $P_\eta \leq P \leq P_{max}$ and $\eta_p \leq \eta \leq \eta_{max}$, where P_η and η_p are, respectively, the power output at the maximum efficiency and efficiency at the maximum power output of the hybrid system.

Table 1 – Parameters used in the SOFC model.

Parameter	Value
Molar enthalpy change at $T = 1223 \text{ K}$, Δh^0 (kJ mol^{-1})	–249.2
Molar Gibbs free energy change at $T = 1223 \text{ K}$, Δg^0 (kJ mol^{-1})	–180.3
Operating pressure, p_0 (atm)	1
Fuel composition pressures, p_{H_2} ; p_{H_2O} (atm)	0.66; 0.34
Air composition pressures, p_{O_2} ; p_{N_2} (atm)	0.21; 0.79
Number of electrons, n_e	2
Faraday constant, F (C mol^{-1})	96,485
Universal gas constant, R ($\text{J mol}^{-1} \text{ K}^{-1}$)	8.314
Activation overpotential:	
Anode exchange current density, $i_{0,a}$ (A m^{-2})	6610
Cathode exchange current density, $i_{0,c}$ (A m^{-2})	3550
Charge transfer coefficient of the electrodes, α	0.5
Ohm overpotential:	
Flowing length in anode: δ_a (cm); a_a ($\Omega \text{ cm}$); b_a (K)	0.01; 0.00298; –1392
Flowing length in cathode: δ_c (cm); a_c ($\Omega \text{ cm}$); b_c (K)	0.22; 0.00811; 600
Flowing length in electrolyte: δ_e (cm); a_e ($\Omega \text{ cm}$); b_e (K)	0.004; 0.00294; 10,350
Flowing length in interconnector: δ_i (cm); a_i ($\Omega \text{ cm}$); b_i (K)	0.0085; 0.12; 4690
Concentration overpotential:	
Limiting current density of H_2 , i_{L,H_2} (A m^{-2})	2.99×10^4
Limiting current density of O_2 , i_{L,O_2} (A m^{-2})	2.16×10^4

4. Several interesting cases

Discussions above only cover a few examples of hybrid systems. Several interesting cases of hybrid systems need to be further researched. As described above, the unified model proposed here also includes the hybrid systems composed of

Table 2 – Parameters used in the MCFC model.

Parameter	Value
Molar enthalpy change at $T = 923 \text{ K}$, Δh^0 (kJ mol^{-1})	247.4
Molar Gibbs free energy change at $T = 923 \text{ K}$, Δg^0 (kJ mol^{-1})	197.0
Partial pressure of H_2 , p_{H_2} (atm)	0.60
Partial pressure of CO_2 in the anode, $p_{CO_2,an}$ (atm)	0.15
Partial pressure of CO_2 in the cathode, $p_{CO_2,ca}$ (atm)	0.08
Partial pressure of H_2O , p_{H_2O} (atm)	0.25
Partial pressure of O_2 , p_{O_2} (atm)	0.08
Activation overpotential:	
Anode exchange current density, $i_{0,a}$ (A m^{-2})	2404
Cathode exchange current density, $i_{0,c}$ (A m^{-2})	602
Ohm overpotential:	
Flowing length in electrolyte: δ_e (cm); a_e ($\Omega \text{ cm}$); b_e (K)	0.17; 2.94; 3016
Reference temperature, T_0 (K)	923

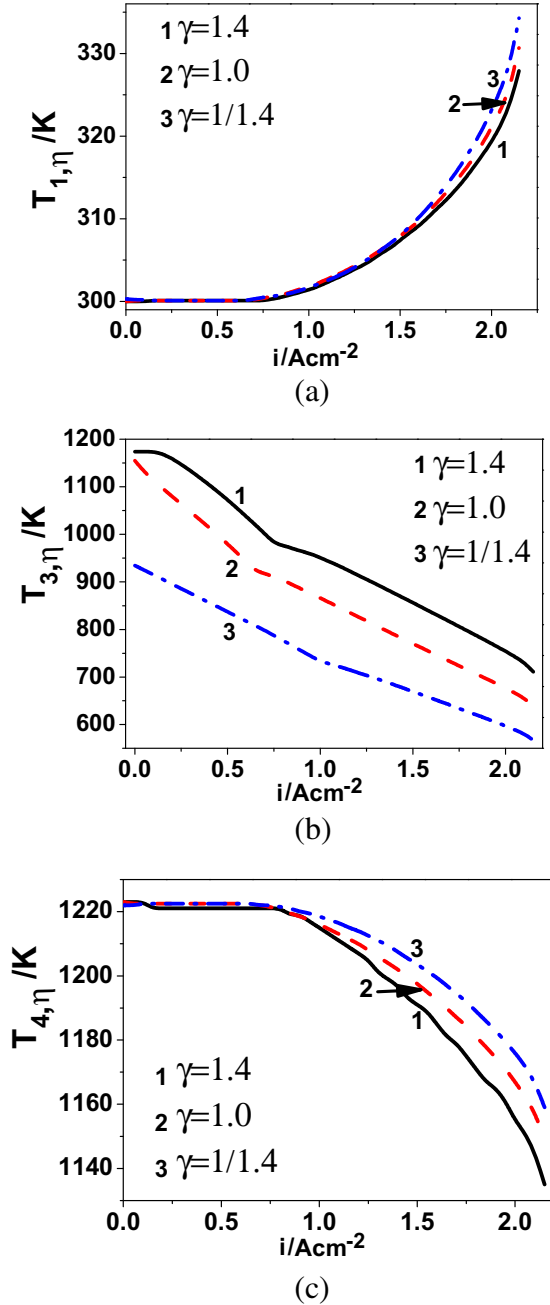


Fig. 3 – The curves of (a) $T_{1,\eta}$, (b) $T_{3,\eta}$, and (c) $T_{4,\eta}$ versus the current density of SOFC-based hybrid systems for the parameters $T = 1223$ K, $T_0 = 300$ K, $K_H = K_R = K_L$, $I = 0.90$, $x = 0.85$, $b_1 = 0.50 \times 10^{-2}$, and $b_2 = 0.50 \times 10^{-4}$. Curves 1, 2, and 3 correspond to the cases of (1) $\gamma = 1.4$, (2) $\gamma = 1.0$, and (3) $\gamma = 1/1.4$, respectively.

high-temperature fuel cells and the Carnot cycle, gas turbine, Braysson cycle, etc. Furthermore, the unified model can be used to discuss the effects of irreversible losses on the performance of hybrid systems.

4.1. The case of $\gamma = 0$

When $c_L \rightarrow \infty$ while c_H remains finite, it is noted that $\gamma = 0$, and the cycle consists of a polytropic, an isothermal, and two

adiabatic processes, constituting exactly the Braysson cycle [79]. In such a case, $T_1 = T_6 = T_5$, there does not exist a regenerative process, and consequently, $T_2 = T_3$. Using the similar method, one can obtain the efficiency and heat input of the heat engine as

$$\eta_h = 1 - \frac{T_1 \ln(T_4 x / T_1)}{I'(T_4 - T_1/x)} \quad (35)$$

and

$$q_1 = \frac{K_H A (T_4 - T_1/x)}{\ln[(T - T_1/x)/(T - T_4)] + (K_H/K_L) T_1 \ln(T_4 x / T_1) / [I'(T_1 - T_0)]}, \quad (36)$$

where $I' = \dot{m} c_H \ln(x T_4 / T_1) / \Delta s$ can be another parameter to describe the internal irreversible losses of the working substance, and Δs is the rate of the entropy change during the low-temperature isothermal process. By searching for the optimum values $T_{1,\eta}$ and $T_{4,\eta}$ of T_1 and T_4 for a given heat input q_1 , one can obtain the maximum efficiency $\eta_{h,m}$ of the heat

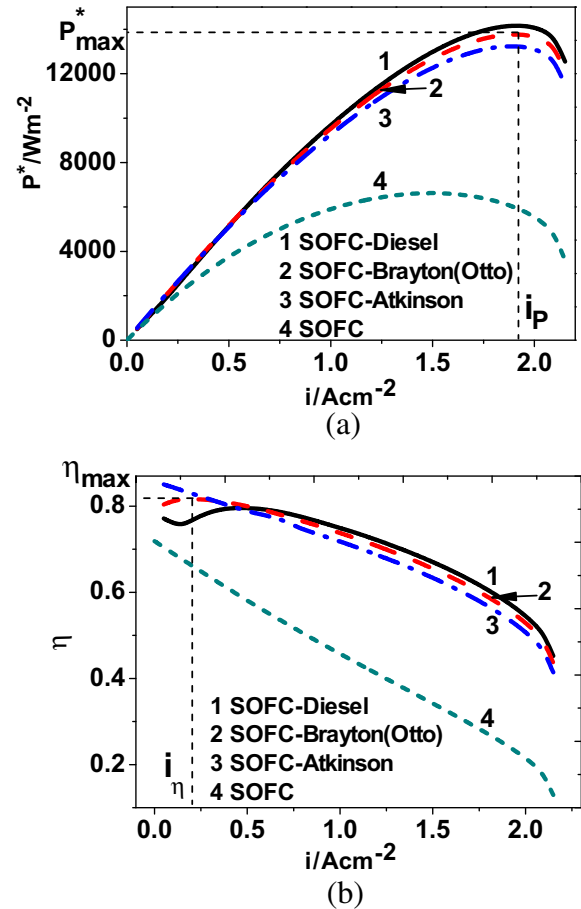


Fig. 4 – The curves of (a) power density and (b) efficiency versus current density of SOFC-based hybrid systems, where i_p and i_η are the current densities at the maximum power density $P_{\max}^*$ and maximum efficiency $\eta_{\max}$, respectively. Curves 1–3 correspond to the cases of $\gamma = 1.4$, $\gamma = 1.0$, and $\gamma = 1/1.4$, respectively. Curve 4 corresponds to the case of the SOFC. The values of other parameters are the same as those used in Fig. 3.

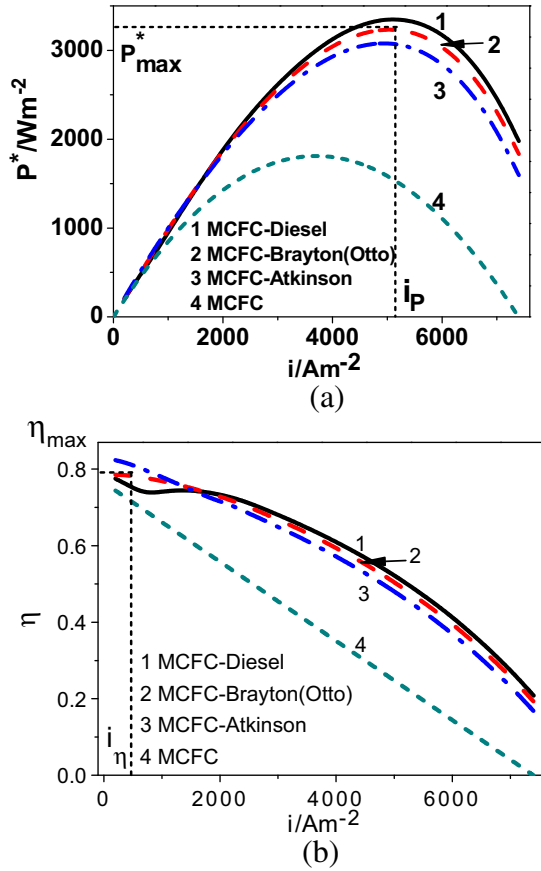


Fig. 5 – The curves of (a) power density and (b) efficiency versus current density of MCFC-based hybrid systems, where $T = 923 \text{ K}$, $T_0 = 300 \text{ K}$, $K_H = K_R = K_L$, $I = 0.91$, $x = 0.85$, $b_1 = b_2 = 0.01$, and i_p and i_{η} are the current densities at the maximum power density $P_{\max}^*$ and maximum efficiency $\eta_{\max}$, respectively. Curves 1–3 correspond to the cases of $\gamma = 1.4$, $\gamma = 1.0$, and $\gamma = 1/1.4$, respectively. Curve 4 corresponds to the case of the MCFC.

engine. Combining Eqs. (31)–(34), one can obtain the performance characteristic curves of high-temperature fuel-cell Braysson engine hybrid systems, as shown by curve 5 in Figs. 6 and 7.

When $I' = 1$, the cycle mode of the heat engine is endoreversible and the performance characteristic curves of high-temperature fuel-cell endoreversible Braysson engine hybrid systems are shown by curve 4 in Figs. 6 and 7. Curves 4 and 5 in Figs. 6 and 7 clearly show that the performance of a fuel-cell endoreversible Braysson engine hybrid system is much better than that of a fuel-cell irreversible Braysson engine hybrid system. It is seen from curves 4 and 5 in Figs. 6 and 7 that for a

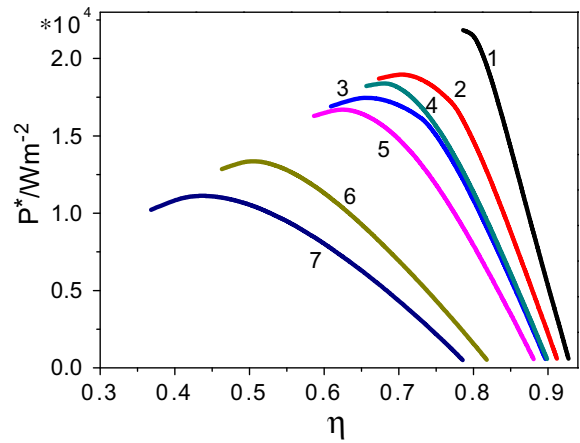


Fig. 6 – The power output versus efficiency curves of SOFC-based hybrid systems, where $x = 0.50$ and $I' = 0.85$. Curves 1, 2, 3, 4, 5, 6, and 7 correspond to the hybrid systems composed of the high-temperature SOFC and the different engines, which are, respectively, (1) Reversible Carnot engine, (2) Endoreversible Carnot engine, (3) Irreversible Carnot engine, (4) Endoreversible Braysson engine, (5) Irreversible Braysson engine, (6) Endoreversible Ericsson engine, and (7) Irreversible Ericsson engine. The values of other parameters are the same as those used in Fig. 3.

engine hybrid system increases, and the hybrid system may be operated around the maximum power output to achieve the optimal performance; while the MCFC Braysson engine hybrid system may be operated in the range from the power output at the maximum efficiency to the maximum power output to achieve the optimal performance.

4.2. The case of $\gamma \rightarrow \infty$

When $c_H \rightarrow \infty$ while c_L remains finite, we note that $\gamma \rightarrow \infty$, $T_2 = T_3 = T_4$, and consequently, $T_6 = T_5$. The heat engine cycle consists of an isothermal, an isobaric, and two adiabatic processes. It is based on an Ericsson cycle for the high-temperature heat addition and a Brayton cycle for the low-temperature heat rejection. Although such a cycle has not been named, its performance has been evaluated [81]. Similar to the Braysson cycle, such a cycle may be simply referred to as the Ericsson cycle. Using the similar method, one can obtain the efficiency and heat input of the heat engine as

$$\eta_h = 1 - \frac{x(T_5 - T_1)}{T_1 I' \ln(T_5/T_1)} \quad (37)$$

and

$$q_1 = \frac{K_H A}{(1/(T - T_1/x)) + (K_H/K_L)x \ln[(T_5 - T_0)/(T_1 - T_0)]/[I' T_1 \ln(T_5/T_1)]}, \quad (38)$$

SOFC-based hybrid system, the power output will increase and then decrease as the efficiency of the SOFC Braysson

where $I' = \Delta \dot{s}/[\dot{m} c_L \ln(T_5/T_1)]$, $\Delta \dot{s}$ is the rate of the entropy change during the high-temperature isothermal process.

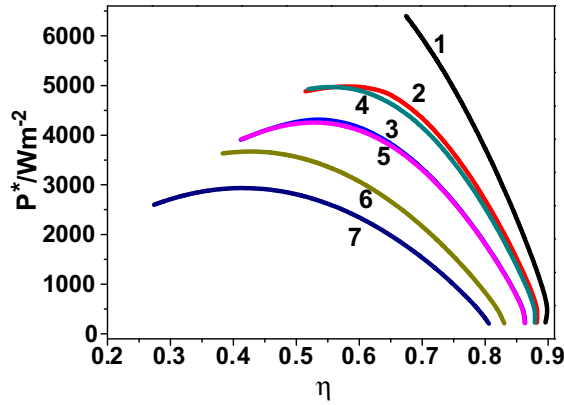


Fig. 7 – The power output versus efficiency curves of MCFC-based hybrid systems where $x = 0.50$ and $I' = 0.85$. Curves 1, 2, 3, 4, 5, 6, and 7 correspond to the hybrid systems composed of the high-temperature MCFC and the different engines, which are, respectively, (1) Reversible Carnot engine, (2) Endoreversible Carnot engine, (3) Irreversible Carnot engine, (4) Endoreversible Braysson engine, (5) Irreversible Braysson engine, (6) Endoreversible Ericston engine, and (7) Irreversible Ericston engine. The values of other parameters are the same as those used in Fig. 5.

Combining Eqs. (31)–(34), (37), and (38), one can obtain the performance characteristic curves of high-temperature fuel-cell Ericston heat engine hybrid systems, as shown by curve 7 in Figs. 6 and 7. Similarly, the performance characteristic curves of high-temperature fuel-cell endoreversible Ericston engine hybrid systems can be plotted by using the condition $I' = 1$, as shown by curve 6 in Figs. 6 and 7. Curves 6 and 7 in Figs. 6 and 7 clearly show that the fuel-cell Ericston engine hybrid system may be operated around the maximum power output to achieve the optimal performance.

4.3. The case of $c_H \rightarrow \infty$ and $c_L \rightarrow \infty$

When $c_H \rightarrow \infty$ and $c_L \rightarrow \infty$, it follows that $T_1 = T_6 = T_5$, $T_2 = T_3 = T_4$, and the heat engine is a Carnot engine. One can obtain the efficiency and heat input of the Carnot engine as [85]

$$\eta_h = 1 - \frac{T_1}{I'T_4} \quad (39)$$

and

$$q_1 = \frac{K_H A (T - T_4)}{1 + \{(K_H/K_L)T_1(T - T_4)/[I'T_4(T_1 - T_0)]\}}, \quad (40)$$

where I' is the ratio of entropy change rates during high- and low-temperature isothermal processes. Combining Eqs. (31)–(34), (39), and (40), one can obtain the performance characteristic curves of high-temperature fuel-cell Carnot engine hybrid systems, as shown by curve 3 in Figs. 6 and 7. By substituting $I' = 1$ into Eqs. (39) and (40), we can also evaluate the performance of high-temperature fuel-cell endoreversible Carnot engine [86,101] hybrid systems and performance characteristic curves are shown by curve 2 in Figs. 6 and 7.

These characteristics are also suitable for the hybrid systems composed of the high temperature fuel cell and the endoreversible Stirling or Ericsson cycle with the ideal regeneration [72]. If we further assume that two heat transfer processes between the working substance in the Carnot engine and two reservoirs are ideal, i.e., $K_H = K_L \rightarrow \infty$, $T_1 = T_0$, and $T = T_4$, the cycle of the heat engine is reversible [28,102], the Carnot efficiency is entirely determined by the temperatures of the fuel cell and environment as

$$\eta_h = 1 - \frac{T_0}{T}. \quad (41)$$

Combining Eqs. (31)–(34), and (41), one can obtain the performance characteristic curves of high-temperature fuel-cell reversible Carnot engine hybrid systems, as shown by curve 1 in Figs. 6 and 7. These characteristics are also suitable for the hybrid systems composed of the high temperature fuel cell and the reversible Stirling or Ericsson cycle with the ideal regeneration [72]. It can be seen from curves 1, 2, and 3 in Figs. 6 and 7 that the performance of a fuel-cell ideal Carnot engine hybrid system is much better than that of a fuel-cell irreversible Carnot engine hybrid system.

4.4. The case of $\gamma = 1$

When $c_H = c_L = c_p$ or $c_H = c_L = c_v$, it is noted that $\gamma = 1$ and the cycle mode of the heat engine may be the Brayton or Otto cycle. For a Brayton cycle, the rate of heat flow in three processes can be expressed as [80]

$$q_1 = \frac{K_H A_H (T_4 - T_3)}{\ln[(T - T_3)/(T - T_4)]} = \dot{m} c_p (T_4 - T_3), \quad (42)$$

$$q_2 = \frac{K_L A_L (T_6 - T_1)}{\ln[(T_6 - T_0)/(T_1 - T_0)]} = \dot{m} c_p (T_6 - T_1), \quad (43)$$

and

$$q_R = K_R A_R (T_5 - T_3) = K_R A_R (T_6 - T_2) = \dot{m} c_p (T_3 - T_2) = \dot{m} c_p (T_5 - T_6), \quad (44)$$

respectively, and the general performance characteristics of such hybrid systems have been shown by curve 2 in Figs. 4 and 5.

4.4.1. The case of $I = 1$

When $I = 1$, the Brayton cycle with the regenerative process is endoreversible, $K_R \rightarrow \infty$, $T_5 = T_3$, $T_6 = T_2$, and $T_2/T_1 = T_4/T_5$. The efficiency and heat input rate of the endoreversible Brayton cycle are, respectively,

$$\eta_h = 1 - \frac{T_1}{xT_4} \quad (45)$$

and

$$q_1 = \frac{AK_H T_4 (1 - x)}{\ln[(T - xT_4)/(T - T_4)] + (K_H/K_L) \ln[(T_1/x - T_0)/(T_1 - T_0)]}. \quad (46)$$

Combining Eqs. (31)–(34), (45), and (46), one can obtain the performance characteristic curves of high-temperature fuel-

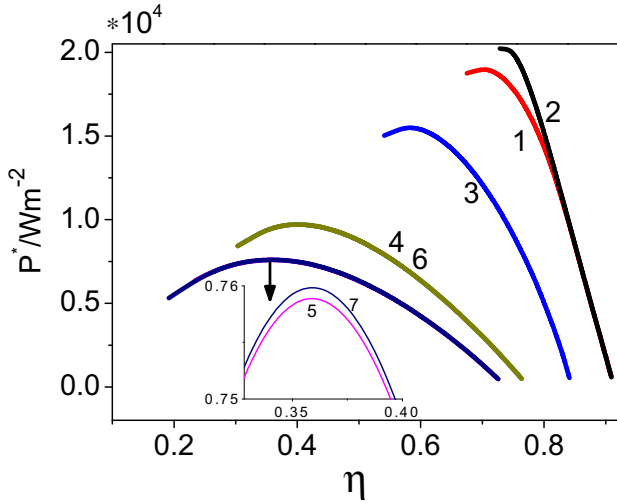


Fig. 8 – The power output versus efficiency curves of SOFC-Brayton engine hybrid systems under different conditions, where $x = 0.80$. Curves 1, 2, 3, 4, 5, 6, and 7 correspond to the cases of (1) Endoreversible Brayton cycle, (2) Endoreversible gas turbine, (3) Irreversible gas turbine, (4) Endoreversible Brayton cycle without the regenerative process, (5) Irreversible Brayton cycle without the regenerative process, (6) Endoreversible gas turbine without the regenerative process, and (7) Irreversible gas turbine without the regenerative process. The values of other parameters are the same as those used in Fig. 3.

cell endoreversible Brayton engine hybrid systems, as shown by curve 1 in Figs. 8 and 9.

4.4.2. The case without regenerative process

If there does not exist a regenerator in the Brayton cycle [103], $K_R = 0$, $T_2 = T_3$, $T_6 = T_5$, and the waste gas from the turbine is directly released to the environment. In such a case, $I = (T_1/T_3)(T_4/T_2)$ and one can obtain the efficiency and heat input rate of the cycle as

$$\eta_h = 1 - \frac{x((T_4/I) - (T_1/x))}{T_4 - T_1/x} \quad (47)$$

and

$$q_1 = \frac{AK_H(T_4 - T_1/x)}{\ln[(T - T_1/x)/(T - T_4)] + (K_H/K_L)\ln[(xT_4/I - T_0)/(T_1 - T_0)]}. \quad (48)$$

Combining Eqs. (31)–(34), (47), and (48), one can obtain the performance characteristic curves of high-temperature fuel-

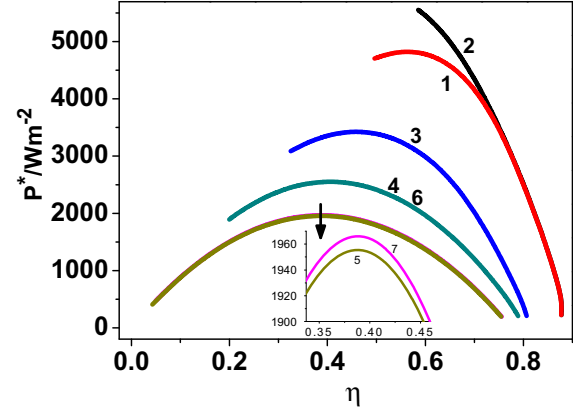


Fig. 9 – The power output versus efficiency curves of MCFC-Brayton engine hybrid systems under different conditions, where $x = 0.80$. Curves 1, 2, 3, 4, 5, 6, and 7 correspond to the cases of (1) Endoreversible Brayton cycle, (2) Endoreversible gas turbine, (3) Irreversible gas turbine, (4) Endoreversible Brayton cycle without the regenerative process, (5) Irreversible Brayton cycle without the regenerative process, (6) Endoreversible gas turbine without the regenerative process, and (7) Irreversible gas turbine without the regenerative process. The values of other parameters are the same as those used in Fig. 5.

cell endoreversible Brayton engine [104] hybrid systems and obtain its performance characteristic curves, as shown by curve 4 in Figs. 8 and 9.

Comparing curves 1 and 4 in Figs. 8 and 9, one can find that the introduction of a regenerator can effectively utilize the waste heat from the turbine and improve the performance of the hybrid system [80].

It should be pointed out that, as long as c_p is replaced by c_v , the results obtained in Sections 4.4–4.4.2 are also suitable for the hybrid systems composed of the high temperature fuel cell and the Otto cycle.

4.4.3. The case of $T_1 = T_0$

When $T_1 = T_0$ and the cycle is an open Brayton cycle, the cycle model can be used to discuss the performance of high-temperature fuel-cell gas-turbine hybrid systems [105,106]. The efficiency and heat input rate of the gas turbine cycle are

$$\eta_h = 1 - \frac{T_0(T_4/I - T_3)}{T_3(T_4 - T_3)} \quad (49)$$

and

$$q_1 = \frac{AK_H(T_4 - T_3)}{\ln[(T - T_3)/(T - T_4)] + (K_H/K_R)(T_3 - T_0/x)/[T_0T_4/(IT_3) - (T_0/x)]}, \quad (50)$$

cell Brayton engine hybrid systems, as shown by curves 4 and 5 in Figs. 8 and 9. Substituting $I = 1$ into Eqs. (47) and (48), one can discuss the performance of the high-temperature fuel-cell

respectively, and the performance characteristic curves of hybrid systems are shown by curve 3 in Figs. 8 and 9. Similarly, one can also obtain the performance characteristic curves of

high-temperature fuel-cell endoreversible gas turbine hybrid systems by introducing the conditions $K_R \rightarrow \infty$, $T_5 = T_3$, $T_6 = T_2$, and $T_2/T_0 = T_4/T_5$, as shown by curve 2 in Figs. 8 and 9. Comparing curves 1, 2, and 3 in Figs. 8 and 9, one can obtain that the performance of a fuel-cell endoreversible gas turbine hybrid system is not only much better than that of a fuel-cell irreversible gas turbine hybrid system but also slightly better than that of a fuel-cell endoreversible Brayton engine hybrid system.

If there does not exist a regenerator in the gas turbine [107], one can obtain the efficiency and heat input rate of the cycle as

$$\eta_h = 1 - \frac{x((T_4/I) - (T_0/x))}{T_4 - T_0/x} \quad (51)$$

and

$$q_1 = \frac{AK_H(T_4 - T_0/x)}{\ln[(T - T_0/x)/(T - T_4)]}, \quad (52)$$

respectively. The performance characteristic curves of the hybrid systems composed of the high-temperature fuel cell and the gas turbine without the regenerative process are shown by curve 7 in Figs. 8 and 9, and the performance characteristic curves of high-temperature fuel-cell endoreversible gas turbine hybrid systems are shown by curve 6 in Figs. 8 and 9. Curves 4–7 in Figs. 8 and 9 show that if there is not any regenerator in the engine cycle, the performance of the fuel-cell gas turbine hybrid system is close to that of a fuel-cell Brayton engine hybrid system.

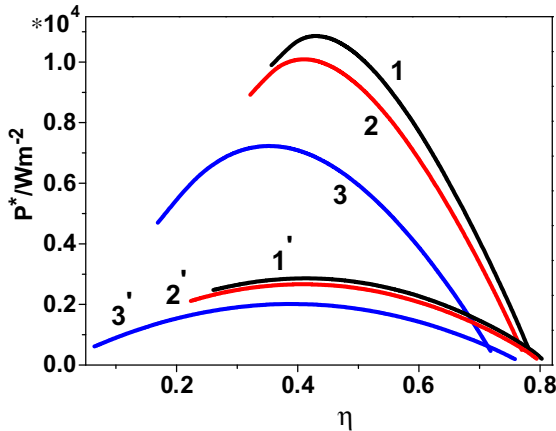


Fig. 10 – The power output versus efficiency curves of high-temperature fuel-cell Diesel engine hybrid systems under different conditions, where $x = 0.70$. Curves 1, 2, and 3 are the performance curves of SOFC-Diesel engine hybrid systems which correspond to the cases of (1) Endoreversible Diesel cycle, (2) Endoreversible Diesel cycle without the regenerative process, and (3) Irreversible Diesel cycle without the regenerative process. Curves 1', 2', and 3' are the performance curves of the MCFC-Diesel engine hybrid system which correspond to the same cases as curves 1, 2, and 3, respectively. The values of other parameters are the same as those used in Figs. 3 and 5.

4.5. The case of $\gamma = c_p/c_v$

When $c_H = c_p$ and $c_L = c_v$, clearly, $\gamma = 1.4$ for diatomic gases [108]. In such a case, the hybrid system is composed of the high-temperature fuel cell and the Diesel engine. The general performance characteristic curves of the hybrid system have been shown by curve 1 in Figs. 4 and 5. Substituting $\gamma = 1.4$, $I = 1$, and $(T_3/T_2)^{1.4} = T_5/T_6$ into Eqs. (24) and (25), one can obtain the efficiency and heat input rate of the endoreversible Diesel engine as

$$\eta_h = 1 - \frac{T_1[(T_4/T_3)^{1.4} - 1]}{1.4(T_4' - T_3)} \quad (53)$$

and

$$q_1 = \frac{AK_H(T_4' - T_3)}{\ln \frac{T - T_3}{T - T_4'} + \frac{K_H}{0.4K_R} \ln \frac{T_1(xT_4'/T_1)^{1.4} - T_3}{T_1(T_4'/T_3)^{1.4} - T_1/x} + \frac{K_H}{1.4K_L} \ln \frac{T_1(T_4'/T_3)^{1.4} - T_0}{T_1 - T_0}}, \quad (54)$$

where $T_4' = [(1.4((T_3/T_1) - 1/x))/((T_1/x)^{-1.4} - T_3^{-1.4})]^{1/1.4}$. Combining Eqs. (31)–(34), (53), and (54), one can obtain the performance characteristic curves of high-temperature fuel-cell endoreversible Diesel engine hybrid systems, as shown by curves 1 and 1' in Fig. 10. Curves 1 and 1' in Fig. 10 and curve 1 in Figs. 4(a) and 5(a) show that the decrease of x may cause the reduction of the power output of a fuel-cell Diesel engine hybrid system.

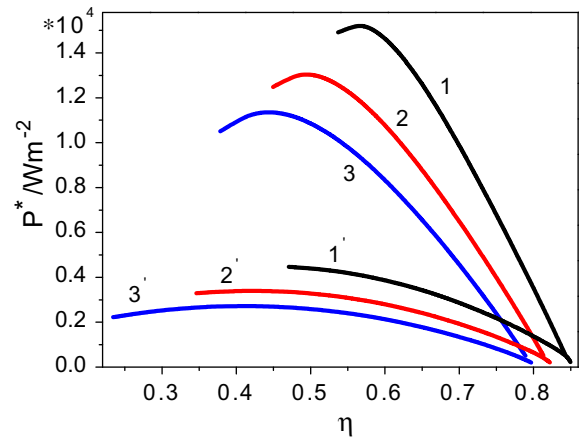


Fig. 11 – The power output versus efficiency curves of high-temperature fuel-cell Atkinson engine hybrid systems under different conditions, where $x = 0.70$. Curves 1, 2, and 3 are the performance curves of the SOFC-Atkinson engine hybrid system which correspond to the cases of (1) Endoreversible Atkinson cycle, (2) Endoreversible Atkinson cycle without the regenerative process, and (3) Irreversible Atkinson cycle without the regenerative process. Curves 1', 2', and 3' are the performance curves of the MCFC-Atkinson engine hybrid system which correspond to the same cases as curves 1, 2, and 3, respectively. The values of other parameters are the same as those used in Figs. 3 and 5.

If there does not exist a regenerator in the Diesel cycle, $K_R = 0$, $T_2 = T_3$, $T_6 = T_5$, and $I = (T_1/T_5)(T_4/T_2)^{1.4}$. From Eqs. (21)–(23), one can obtain the efficiency and heat input rate of the cycle as

$$\eta_h = 1 - \frac{T_1(xT_4/T_1)^{1.4}/I - T_1}{1.4(T_4 - T_1/x)} \quad (55)$$

and

$$q_1 = \frac{AK_H(T_4 - T_1/x)}{\ln[(T - T_1/x)/(T - T_4)] + [K_H/(1.4K_L)] \ln \left\{ \left[(T_1(xT_4/T_1)^{1.4})/I - T_0 \right] / (T_1 - T_0) \right\}}. \quad (56)$$

If there does not exist a regenerator in the Atkinson cycle [82], then $K_R = 0$, $T_2 = T_3$, $T_6 = T_5$, and $I = (T_1/T_5)(T_4/T_2)^{5/7}$. From Eqs. (21)–(23), one can obtain the efficiency and heat input rate of the cycle as

$$\eta_h = 1 - \frac{7T_1[(xT_4/T_1)^{5/7}/I - 1]}{5(T_4 - T_1/x)} \quad (59)$$

and

$$q_1 = \frac{AK_H(T_4 - T_1/x)}{\ln[(T - T_1/x)/(T - T_4)] + [7K_H/(5K_L)] \ln \left\{ \left[(T_1(xT_4/T_1)^{5/7})/I - T_0 \right] / (T_1 - T_0) \right\}}. \quad (60)$$

Using Eqs. (31)–(34), (55) and (56), one can obtain the performance characteristic curves of high-temperature fuel-cell Diesel engine hybrid systems, as shown by curves 3 and 3' in Fig. 10. Substituting $I = 1$ into Eqs. (55) and (56), one can obtain the hybrid systems composed of the high-temperature fuel cell and the endoreversible Diesel engine with no regenerator [109], and performance characteristic curves are shown by curves 2 and 2' in Fig. 10. Curves 1, 1', 2, and 2' in Fig. 10 show the excellence of the fuel-cell Diesel engine hybrid systems with the regenerator.

4.6. The case of $\gamma = c_v/c_p$

When $c_H = c_v$ and $c_L = c_p$, we note that $\gamma = 5/7$ for diatomic gases. In such a case, the hybrid system is composed of the high-temperature fuel cell and the Atkinson engine. The general performance characteristic curves of hybrid systems have been shown by curve 3 in Figs. 4 and 5. Substituting $\gamma = 5/7$, $I = 1$, and $(T_3/T_2)^{5/7} = T_5/T_6$ into Eqs. (24) and (25), one can obtain the efficiency and heat input rate of the endoreversible Atkinson engine as

$$\eta_h = 1 - \frac{7T_1[(T_4'/T_3)^{5/7} - 1]}{5(T_4' - T_3)} \quad (57)$$

and

$$q_1 = \frac{AK_H(T_4' - T_3)}{\ln \frac{T - T_3}{T - T_4'} + \frac{7K_H}{2K_R} \ln \frac{T_1(T_4'/T_3)^{5/7} - T_1/x}{T_1(xT_4'/T_1)^{5/7} - T_3} + \frac{7K_H}{5K_L} \ln \frac{T_1(T_4'/T_3)^{5/7} - T_0}{T_1 - T_0}}, \quad (58)$$

where $T_4' = [(((T_3/T_1) - (1/x))(5/7))/((T_1/x)^{-5/7} - T_3^{-5/7})]^{7/5}$. Combining Eqs. (31)–(34), (57), and (58), one can obtain the performance characteristic curves of high-temperature fuel-cell endoreversible Atkinson engine hybrid systems, as shown by curves 1 and 1' in Fig. 11.

Using Eqs. (31)–(34), (59), and (60), one can obtain the performance characteristic curves of high-temperature fuel-cell Atkinson engine hybrid systems, as shown by curves 3 and 3' in Fig. 11. Substituting $I = 1$ into Eqs. (59) and (60), one can discuss the performance of the hybrid systems composed of the high-temperature fuel cell and the endoreversible Atkinson engine without a regenerative process and can generate the performance characteristic curves, as shown by curves 2 and 2' in Fig. 11. The curves in Fig. 11 show that the power output will increase and then decrease as the efficiency of a fuel-cell Atkinson engine hybrid system increases, and the hybrid system may be operated around the maximum power output to achieve the optimal performance of the hybrid system.

5. Conclusions

In this study, the performances of various high-temperature fuel cells, heat engines, and their hybrid systems are reviewed. A new unified model of high-temperature fuel-cell heat-engine hybrid systems is proposed. In detail, the performance of hybrid systems is studied by considering the irreversibilities primarily caused by overpotentials and heat leakage in high-temperature fuel cells, finite-rate heat transfer between the working substance and the heat reservoirs, and internal losses of the working substance in heat engines. The performance characteristic curves of high-temperature fuel cells and hybrid systems are, respectively, obtained. The optimally working regions of some of the important performance parameters of hybrid systems are determined. Some interesting cases of hybrid systems are also discussed in detail. The results obtained show that hybrid systems can effectively utilize the high temperature waste heat and improve both the power output and the efficiency of high-temperature fuel cells.

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